

On the excess in the inclusive $W^+W^- \rightarrow l^+l^-\nu\bar{\nu}$ cross section

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Abstract In this note we analyse the excess in the W^+W^- *inclusive* cross section recently measured at the LHC. We point out that in fact for the ATLAS *fiducial* cross sections there is no excess in the measurements compared to the NLO QCD predictions. We also argue that higher order effects to the fiducial cross section are small, and tend to cancel each other, hence the inclusion of NNLO and NNLL corrections will not modify this agreement significantly. We find that at 8 TeV a substantial part of the disagreement with the NLO prediction for the total cross section observed by ATLAS is due to the extrapolation carried out with POWHEG.

1 Introduction

The inclusive W^+W^- cross section at 7 and 8 TeV has been measured recently by both the ATLAS [1,2] and CMS collaborations [3,4]. All measurements show a systematic tension when compared to next-to-leading order (NLO) QCD calculations. The disagreement was first observed in the 7 TeV data, and then it increased at 8 TeV, where the tension with the NLO predictions reaches the $2 - 2.5\sigma$ level. The small uncertainties quoted for the NLO calculations suggest that higher-order QCD corrections can not change this pattern. This triggered a lot of interest and a number of models were suggested to explain this excess in terms of new light states, see e.g. refs. [5–9]. However, before discussing any hint for New Physics, one needs to fully control the uncertainty associated with the Standard Model prediction.

One issue that arises, is that refs. [1–4] quote the inclusive cross section, obtained by extrapolating the measured fiducial cross section through data driven Monte Carlo (MC) acceptances. One reason for quoting the inclusive cross-section is that it is independent of the experimental setup, hence it is possible to make statements about whether two measurements by ATLAS and CMS are in agreement, while fiducial cross-sections are different for the two experiments. Nevertheless, the extrapolation from the fiducial to the inclusive phase space relies on a Monte Carlo simulation, and thus obviously it depends on the generator used. For instance, a generator that systematically underestimates the fiducial cross-section would lead to an overestimation of the resulting “measured” inclusive cross section. Hence, a comparison to theory should be made first in the fiducial region, for which experimental data is available, before extrapolating the result to the fully inclusive phase space. A possible way to compare the measurements of both experiments avoiding a big extrapolation to the total inclusive phase space would be to extrapolate the ATLAS fiducial measurement from the CMS one, and vice versa. This extrapolation would still depend on the Monte Carlo generator used, but it would involve two cross sections that are typically of the same order of magnitude.

In this note we compare the measured fiducial cross sections to the NLO predictions and find that there is no sizable tension between the two (at the $1\text{-}\sigma$ level). We then study the effect of the extrapolation from the fiducial region to the inclusive one. We find that the Monte Carlo acceptance computed with POWHEG overestimates the reduction due to the fiducial phase space cuts, leading to a larger total cross section when the extrapolation from the fiducial to the inclusive phase space is carried out. We study the source of the reduction in the Monte Carlo prediction, and discuss the possible impact of higher-order corrections. At the moment, only ATLAS published the measured fiducial cross sections at 7 and 8 TeV. Since the larger disagreement is observed in the 8 TeV data, we focus on the latter measurement for the three leptonic channels, e^+e^- , $\mu^+\mu^-$ and $e^+\mu^- + e^-\mu^+$.

2 Comparison to Next to Leading Order prediction

We present here theory predictions for the fiducial cross section as defined by the ATLAS experiment at a centre-of-mass energy of 8 TeV [2]. The relative fiducial cuts are summarized in Table 1. Our analysis equally applies to the 7 TeV case, for which we find similar conclusions.

It is instructive to first compare the fiducial measurements to the next-to-leading order results from MCFM 6.6 [11], including the formally next-to-next-to-leading order (NNLO) contribution due to $gg \rightarrow W^+W^-$ [12]. We

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8 TeV fiducial region
$p_t > 25(20)$ GeV for the leading (subleading) lepton and charged leptons separated by $\Delta R > 0.1$ muon pseudorapidity $ y < 2.4$ and electron pseudorapidity $ y < 1.37$ or $1.52 < y < 2.47$ no jets (anti- k_t [10], $R = 0.4$) with $p_t > 25$ GeV and $ y < 4.5$, separated from the electron by $\Delta R > 0.3$ $m_{ll'} > 15, 15, 10$ GeV and $ m_{ll'} - m_Z > 15, 15, 0$ GeV for ee , $\mu\mu$, and $e\mu$, respectively $p_{t,\text{Rel}}^{\nu+\bar{\nu}} > 45, 45, 15$ GeV and $p_t^{\nu+\bar{\nu}} > 45, 45, 20$ GeV for ee , $\mu\mu$, and $e\mu$, respectively

Table 1 Fiducial volume, as defined by the ATLAS collaboration, at 8 TeV. For a detailed definition of all variables see [2].

work in the G_μ scheme with the electroweak parameters $M_Z = 91.1876$ GeV, $\Gamma_Z = 2.4952$ GeV, $M_W = 80.398$ GeV, $\Gamma_W = 2.1054$ GeV, and $G_F = 1.16639 \times 10^{-5}$ GeV⁻². The branching ratio of W into leptons is taken from the Particle Data Book [13], namely $\text{Br}(W \rightarrow l\nu) = 0.108$.¹ We use the MSTW2008nlo parton densities [14] and central renormalization and factorization scales $\mu_R = \mu_F = M_{4l}$, where M_{4l} is the invariant mass of the leptonic system. The scale uncertainty is obtained by varying both scales by a factor of two in either direction and keeping $\mu_R = \mu_F$. With this setup we get a total inclusive W^+W^- cross section of $53.6^{+1.4}_{-1.0}$ pb ($56.5^{+1.5}_{-1.1}$ pb) excluding (including) Higgs mediation. For consistency, the quoted Higgs mediated cross section has also been computed with MCFM. On the other hand, ATLAS finds $71.4^{+1.2}_{-1.2}(\text{stat.})^{+5.0}_{-4.4}(\text{syst.})^{+2.2}_{-2.1}(\text{lumi.})$ pb.

The measured fiducial cross sections at 8 TeV are reported in the first column of Table 2, together with the total NLO predictions in the fourth column. The latter is given by the sum of the cross-section without Higgs mediation and the Higgs mediated contribution, as reported in the second and third column, respectively. The quoted theory uncertainty does not account either for the PDF error, that was found to be at 5% level [2], or for any interference effect.

	ATLAS @ 8 TeV	$pp \rightarrow l^+l^-\nu\bar{\nu}$	$pp \rightarrow H \rightarrow l^+l^-\nu\bar{\nu}$	total
$e^+\mu^- + e^-\mu^+$	$377.8^{+6.9}_{-6.8}(\text{stat.})^{+25.1}_{-22.2}(\text{syst.})^{+11.4}_{-10.7}(\text{lumi.})$	$332.4^{+4.7}_{-2.3}$	$9.8^{+0.0}_{-1.2}$	$342.2^{+4.7}_{-2.6}$
e^+e^-	$68.5^{+4.2}_{-4.1}(\text{stat.})^{+7.7}_{-6.6}(\text{syst.})^{+2.1}_{-2.0}(\text{lumi.})$	$63.7^{+0.8}_{-0.4}$	$2.2^{+0.0}_{-0.2}$	$65.9^{+0.8}_{-0.4}$
$\mu^+\mu^-$	$74.4^{+3.3}_{-3.2}(\text{stat.})^{+7.0}_{-6.0}(\text{syst.})^{+2.3}_{-2.1}(\text{lumi.})$	$69.3^{+0.9}_{-0.4}$	$2.4^{+0.0}_{-0.2}$	$71.7^{+0.9}_{-0.5}$

Table 2 ATLAS fiducial cross-sections in fb at 8 TeV (1st column) and two processes that contribute to W^+W^- production (2nd and 3rd column). The last column contains the sum of the previous two contributions. The theory predictions are obtained with MCFM with central renormalisation and factorisation scales set to the leptonic system invariant mass, and using the MSTW2008nlo PDF set. The (formally NNLO) $gg \rightarrow W^+W^-$ channel is included. Following ref. [2], all quoted numbers do not include electrons or muons coming from τ decays.

The quoted theoretical uncertainties obtained by varying renormalisation and factorisation scales are tiny, at the level of just about 1-1.5%. However, the definition of the fiducial volume involves a veto on jets with a large transverse momentum (see Table 1). It is well-known that, in the presence of a jet-veto, fixed-order calculations typically underestimate the true theoretical uncertainty, and a more sophisticated procedure should be used in order to assess the uncertainty [15, 16]. Since at the moment the by far dominant uncertainty is the systematic one, and since several theoretical improvements are now possible on the theory numbers quoted above (inclusion of NNLL resummation effects [7] matched to exact NNLO predictions [17]), we do not try to quantify the theory error in a more precise way. Yet, we observe that there is no sizable tension between NLO theory and experiment within the large systematic uncertainties. The level of agreement depends on the leptonic channel considered, and it is always at the one σ level, or better.

In the following section we rather study how much the Monte Carlo prediction differs from the pure NLO one for the fiducial cross section. The ATLAS analysis at 8 TeV use the POWHEG, so we consider this generator in the following section.

3 Resummation and Parton Shower effects

In the present section we investigate the effect of parton shower and hadronisation on the fiducial cross section using the POWHEG BOX [18–20] (using its default settings), where the NLO prediction for W^+W^- production is matched to a parton shower [21, 22]. Events are showered with Pythia 6.4.28 [23], Perugia tune 350 [24] (unless otherwise stated), and hadronisation and underlying event effects are included. To estimate the impact of parton shower and

¹We stress that the experimental errors in the electroweak parameters are an important source of theory uncertainty. The sole variation of the W -boson width Γ_W within its error, as quoted by the PDG $\Gamma_W = 2.085 \pm 0.042$ leads to a $\sim 8.5\%$ variation in the total cross section, since it scales as $\sigma_{WW} \sim 1/(\Gamma_W M_W)^2$. However, the Standard Model calculation of the W width has a much smaller uncertainty.

hadronisation we compare the latter prediction to the NLO result obtained within the **POWHEG** programme itself. Unlike in the previous section, and for the sake of simplicity, we do not include the gg -initiated channel here since it is not implemented in the **POWHEG BOX**.

From Table 3 it is evident that the shower and hadronisation reduce the fiducial cross section systematically in all channels and at both energies by about 9-11%. The uncertainties with **POWHEG** are obtained by varying μ_R and μ_F by a factor of two in either direction around M_{4l} , while keeping $\mu_R = \mu_F$. In the presence of a parton

$pp \rightarrow l^+ l^- \nu \bar{\nu}$ (no gg)	POWHEG (hadron)	POWHEG (NLO)	ratio
$e^+ \mu^- + e^- \mu^+$	$295.2^{+4.8}_{-2.8}$	$323.0^{+6.0}_{-6.5}$	0.91
$e^+ e^-$	$54.8^{+1.7}_{-0.7}$	$61.5^{+1.2}_{-1.3}$	0.89
$\mu^+ \mu^-$	$59.5^{+1.7}_{-0.2}$	$66.9^{+1.3}_{-1.6}$	0.89

Table 3 Comparison between **POWHEG** at hadron level and its NLO prediction with fiducial cuts of ATLAS at 8 TeV. Cross-sections are given in fb. Neither the gg -initiated process nor the Higgs-mediated one are included. The central scales are set to the leptonic system invariant mass and the MSTW2008nlo PDF are used. Uncertainties are obtained as explained in the text.

shower, competing effects will change the hardest jet transverse momentum, e.g. events will typically have more jets, while MPI and out of jet radiation can affect the hardest jet transverse momentum. So it is reasonable to expect differences between the pure NLO and **POWHEG** prediction, especially given that the hardest jet kinematics is described at leading order only in both cases. Yet, the observed 9-11% effect is larger than what one would expect for a process that at Born level is quark-initiated and involves no final state QCD hard jets.

To study the impact of the jet veto, we consider the inclusive jet-veto efficiency where no further cuts on leptons are applied. The results are reported in Figure 1 for three different **Pythia** tunes. We observe that the suppression of the **POWHEG** prediction with respect to the pure NLO at $p_{t,\text{veto}} = 25$ GeV depends on the tune, and it varies in the range 6-9%. In order to check whether **POWHEG** overestimates Sudakov suppression effects, one can compare

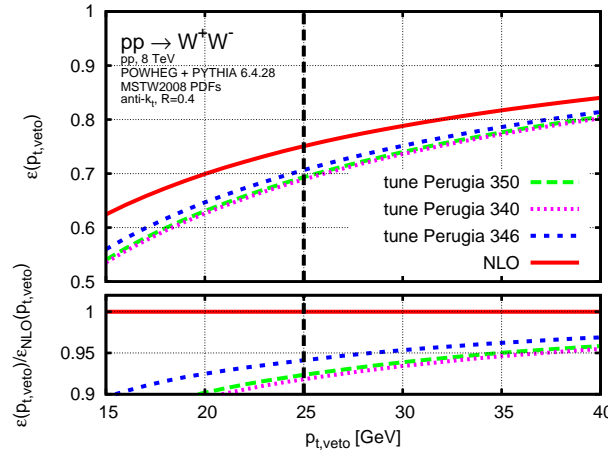


Fig. 1 Jet-veto efficiency for W^+W^- production obtained with the **POWHEG BOX** both at pure NLO and matched to parton shower simulated with **Pythia** 6.4.28. For comparison, different tunes are shown.

the Monte Carlo prediction to the analytic resummation for the jet-veto efficiency. Recently a NNLL resummation for the jet veto efficiency was carried out for this process [25], where it is shown that the NNLL+NLO jet-veto efficiency is larger than the NLO one by a few percent, however a matching of the NNLL and NNLO calculation has not been done yet. It is possible to provide an estimate of the NNLL+NNLO corrections by looking at the jet-veto resummation for Drell-Yan [16]. The difference between Z and W^+W^- production is mainly due to a different invariant mass for the colourless final state, different parton luminosities, and the absence of a t channel in Z production at the Born level. As far as the jet-veto efficiency is concerned, at small $p_{t,\text{veto}}$, where the logarithmic terms dominate, the main difference between the two processes is due to the masses of the colourless final state (which is the natural mass scale appearing in the large logarithms). This is due to the fact that in the efficiency differences in the virtual corrections and parton luminosities largely cancel, while the real radiation pattern is the same in both processes. Moreover, the dependence on electroweak parameters also cancels in the efficiency at small $p_{t,\text{veto}}$. To convert the jet veto efficiency from Z to W^+W^- production, neglecting for the moment the gg contribution, we impose that the argument of the large logarithms is the same for both processes. In both cases, the cross section is integrated over the invariant mass of the colourless final-state objects. Since the invariant mass spectrum is peaked at M_Z and $2M_W$, respectively, and it steeply decreases for larger invariant masses, we assume that the integral is dominated by the value of the distribution at the peak and we thus consider the respective masses as argument of the Sudakov logarithms. This leads to

$$\frac{p_{t,\text{veto}}^{DY}}{M_Z} = \frac{p_{t,\text{veto}}^{WW}}{2M_W}. \quad (1)$$

Since ATLAS uses a veto of $p_{t,\text{veto}}^{WW} = 25$ GeV, one obtains $p_{t,\text{veto}}^{DY} \sim 15$ GeV. We emphasize that, because of this small $p_{t,\text{veto}}$, the logarithmic terms are expected to dominate over the finite remainder. This correspondence can be tested with POWHEG by comparing the jet-veto efficiency for the two processes. In order to study the Sudakov region in a shower-independent way, we perform the comparison at the Les Houches Event (LHE) level in Figure 2, where $p_{t,\text{veto}}^{WW}$ has been rescaled by $M_Z/(2M_W)$ according to Eq. 1. We see that after the rescaling the two efficiencies are

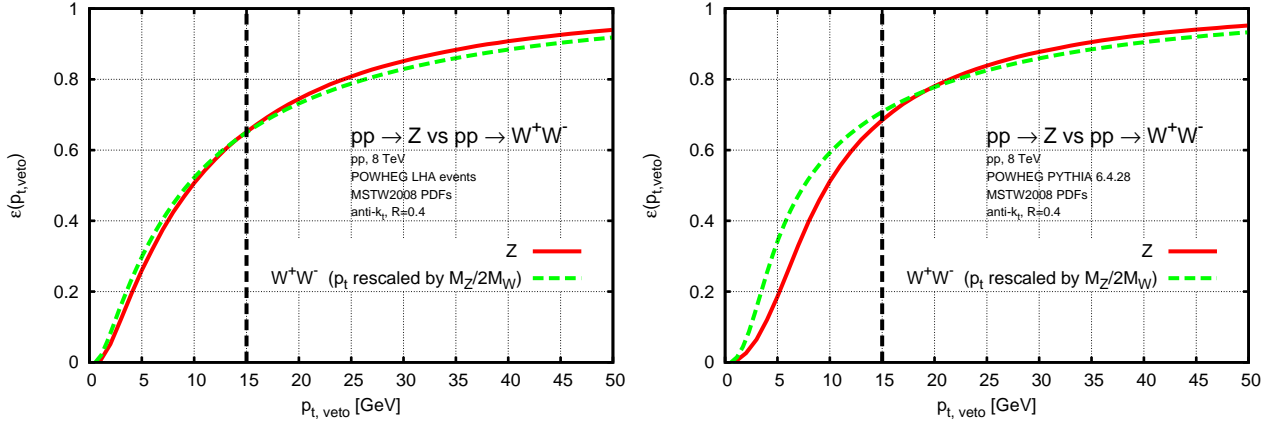


Fig. 2 Jet-veto efficiency for Z production obtained with the POWHEG BOX and showered with Pythia (v. 6.4.28 Perugia tune 350).

in good agreement in the small transverse momentum region. Not surprisingly, when the Pythia parton shower and non-perturbative effects (including hadronisation, multiple interactions, pile-up and intrinsic p_t simulation) are also included, the above agreement is partly lost (right plot in Figure 2), since some non-perturbative corrections and non-logarithmic corrections have a different scaling in p_t . Still, we can use the relation between $p_{t,\text{veto}}^{WW}$ and $p_{t,\text{veto}}^{DY}$ to estimate the impact of higher-order logarithmic corrections on the jet-veto efficiency by looking at the corresponding quantity in Z -boson production at $p_{t,\text{veto}} = 15$ GeV, shown in Figure 3 (left).

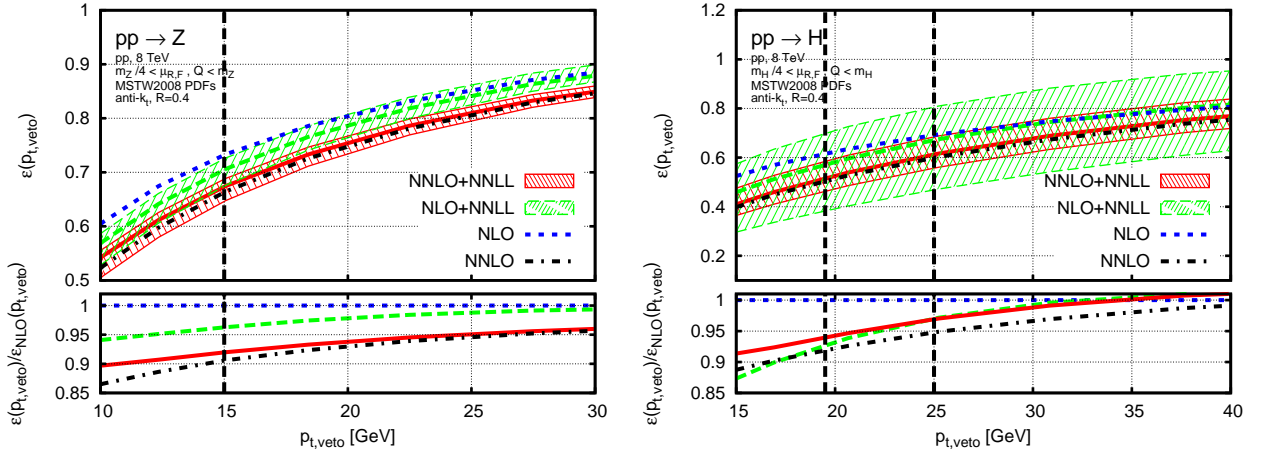


Fig. 3 Jet-veto efficiency for single Z (left) and H (right) production. The uncertainty band for the resummed predictions is obtained by varying μ_R , μ_F , and the resummation scale Q by a factor of two in either direction while keeping $1/2 < \mu_R/\mu_F < 2$. Moreover, the matching scheme for the jet-veto efficiency is also varied as shown in ref. [16]. The dashed black lines denote the $p_{t,\text{veto}}$ values relevant for the present analysis (see text for more details).

By comparing the pure NLO (blue dashed line) and the NLO+NNLL (green dashed line) calculation of Drell Yan at this transverse momentum value, one observes a suppression by about 3-4% when NNLL effects are included. While the magnitude of the impact of the NNLL resummation is found to be similar to that of ref. [25], we observe a reduction in the jet-veto efficiency rather than an enhancement. This might be due to a different matching scheme and treatment of higher-order corrections. Furthermore, we observe that POWHEG enhances considerably Sudakov effects with respect to the analytic resummation when compared to the NLO prediction. On the other hand, it is also clear from Fig. 3 that the difference with respect to NLO is about -7-8% when the NNLL is matched to the NNLO result (red solid line). Hence, as far as jet-veto effects are concerned, POWHEG is accidentally close to the NNLL+NNLO prediction at this veto scale. Therefore, the inclusive cross section extrapolated using POWHEG will be reasonably in better agreement with the NNLO prediction, rather than with the NLO one.

A further reduction in the fiducial cross section is due to the way the hardest emission is treated in POWHEG, which was found to slightly change the transverse momentum spectrum of the produced leptons. As example, we show in Fig. 4 the comparison between the Les Houches events and the pure NLO for the missing transverse

momentum $p_{t,\text{miss}}$ and the $p_{t,\text{Rel}}^{\nu+\bar{\nu}}$ efficiencies. We find that for the specific fiducial cuts the overall effect amounts to the remaining $\sim 3\%$ reduction. The latter effect is not enhanced further by the parton shower, which does not change substantially the kinematics of leptons. This difference is due to higher-order effects, however it leads to a lower fiducial cross sections at LHE or parton-shower level in comparison to pure NLO. This difference should be interpreted as a systematic uncertainty associated with the Monte Carlo generator.²

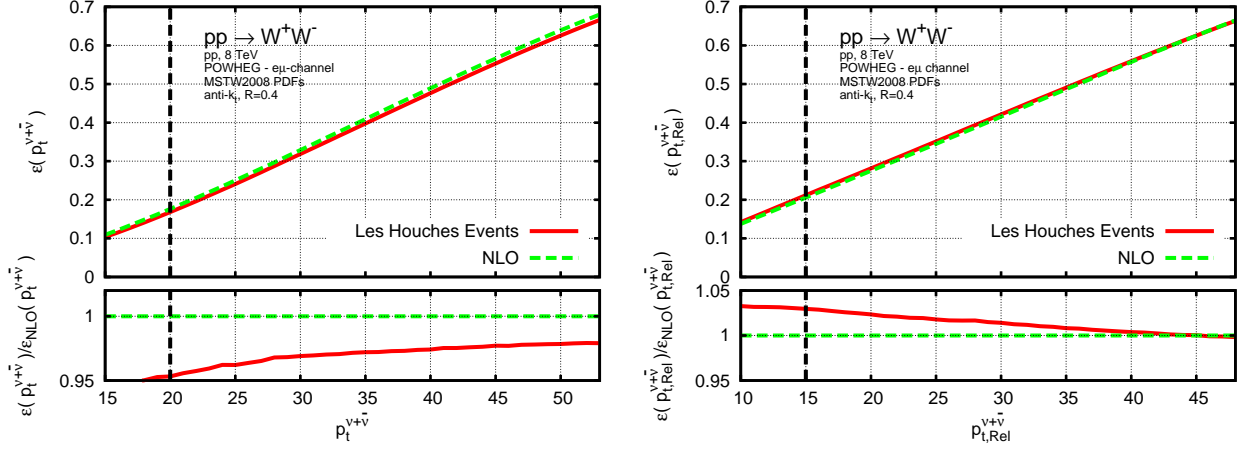


Fig. 4 Efficiencies with a cut in either leading lepton's $p_t^{\nu+\bar{\nu}}$ (left) or $p_{t,\text{Rel}}^{\nu+\bar{\nu}}$ (right). The plots report the comparison between LHE events and the pure NLO prediction, showing a systematic reduction at the LHA level for the actual fiducial cuts (black dashed lines).

We can provide an estimate for the fiducial cross section using the information on the NNLL+NNLO jet veto efficiency, and on the NNLO inclusive cross section, and assuming that QCD higher order corrections do not affect the lepton acceptances. The resulting fiducial cross section can be expressed as

$$\sigma_{\text{fid.}}^{\text{th.}} = \sum_{c \in \text{channel}} \sigma_{\text{fid.}}^{(c),\text{NLO}} \times \frac{\epsilon^{(c),\text{NNLL+NNLO}}(p_{t,\text{veto}}^{(c)})}{\epsilon^{(c),\text{NLO}}(p_{t,\text{veto}}^{(c)})} \times \frac{\sigma_{\text{incl.}}^{(c),\text{NNLO}}}{\sigma_{\text{incl.}}^{(c),\text{NLO}}}, \quad (2)$$

where the sum is performed over the three different channels, i.e. $q\bar{q} \rightarrow W^+W^-$, $gg \rightarrow W^+W^-$, and $gg \rightarrow H \rightarrow W^+W^-$. Using Figs. 3, one can give an estimate of the jet veto efficiencies at the three relevant $p_{t,\text{veto}}^{(c)}$ scales. For the $q\bar{q} \rightarrow W^+W^-$ channel, we consider the Drell-Yan efficiencies at $p_{t,\text{veto}}^{q\bar{q}} = 15 \text{ GeV}$, while for the $gg \rightarrow W^+W^-$ and $gg \rightarrow H \rightarrow W^+W^-$ channels we consider the Higgs production efficiencies at $p_{t,\text{veto}}^{gg \rightarrow WW} = 19.5 \text{ GeV}$, and $p_{t,\text{veto}}^{gg \rightarrow H \rightarrow WW} = 25 \text{ GeV}$, respectively. The NLO cross sections are taken from **MCFM**, while the NNLO cross sections are taken from ref. [17]. We obtain the fiducial cross sections reported in Table 4. The theory uncertainties have been obtained by combining in quadrature the symmetrized errors in the **MCFM** cross sections, estimated jet-veto efficiencies, and NNLO total cross section, respectively. For a more reliable estimate of the uncertainty, one could use one of the methods available in the literature [15, 16, 27]. We observe that the estimated fiducial cross sections are in very good agreement with data. Therefore, also the extrapolated inclusive cross section will be in agreement with the NNLO prediction.

decay mode	$\sigma_{\text{fid.}}^{\text{exp.}} [\text{fb}]$	$\sigma_{\text{fid.}}^{\text{th.}} [\text{fb}]$
$e^+\mu^- + e^-\mu^+$	$377.8^{+6.9}_{-6.8}(\text{stat.})^{+25.1}_{-22.2}(\text{syst.})^{+11.4}_{-10.7}(\text{lumi.})$	$357.9^{+14.4}_{-14.4}$
e^+e^-	$68.5^{+4.2}_{-4.1}(\text{stat.})^{+7.7}_{-6.6}(\text{syst.})^{+2.1}_{-2.0}(\text{lumi.})$	$69.0^{+2.7}_{-2.7}$
$\mu^+\mu^-$	$74.4^{+3.3}_{-3.2}(\text{stat.})^{+7.0}_{-6.0}(\text{syst.})^{+2.3}_{-2.1}(\text{lumi.})$	$75.1^{+3.0}_{-3.0}$

Table 4 Comparison between the measured fiducial cross section and the theory prediction with estimated NNLL+NNLO effects. Theory uncertainties have been symmetrized and combined in quadrature.

4 Conclusions

Despite the substantial tension with the NLO prediction reported by ATLAS for the inclusive W^+W^- cross section at 8 TeV, our findings show that the measured fiducial cross sections are in good agreement (at about the $1\text{-}\sigma$ level) with the NLO result for all leptonic decay modes.

²It is possible to quantify this systematic uncertainty by varying in the **POWHEG BOX** code the parameter **hdamp** [26], which controls the amount of real radiation included in the Sudakov form factor.

The discrepancy observed by ATLAS at 8 TeV can be explained to a large extent by studying the Monte Carlo predictions used in the extrapolation to the inclusive cross section. The prediction obtained with the **POWHEG BOX** reduces the NLO result by 9-11%. The Monte Carlo result for the jet-veto efficiency is found to overestimate Sudakov suppression effects with respect to the analytic resummation. Furthermore, at the Les Houches level, the leptons' transverse momentum spectrum is slightly different than the NLO distribution. This is a higher-order effect, and it leads to a systematic reduction in the fiducial cross section (of about 3% in the present case) at the parton-shower level with respect to NLO. As a result, the fiducial cross-section is reduced and the extrapolated ("measured") inclusive cross section tends to be overestimated. The latter effect should be taken into account as a potential additional systematic uncertainty associated with the matching procedure of higher-order calculations to a parton shower.

Using the NNLL+NNLO predictions for Drell-Yan and Higgs production, we provide an estimate for the fiducial cross section, including these higher-order effects. It suggests that the agreement found at NLO for the fiducial cross sections will remain good, or even improve once NNLL+NNLO effects are included in the theory predictions. A better assessment of higher order effects and related uncertainties is today possible by matching the recently computed NNLO corrections [17] to the existing NNLL resummation [25]. It would be also useful to encode the NNLO prediction in a fully exclusive NNLO + parton shower generator, on the line of what has been recently done for Higgs- [28, 29] and Drell-Yan production [30, 31].³ Further studies are also required for the formally NNLO gg -initiated channel. At lowest order it amounts to 3-4% of the NLO cross section at the inclusive level (i.e. of the same order of the Higgs-mediated reaction), but it raises to 8-9% after fiducial cuts are taken into account since the jet veto is ineffective when applied to the tree level prediction. Due to the large amount of initial state radiation, this channel will experience a sizable Sudakov suppression, and has a potentially large K factor. We estimate the NNLL+NNLO effects in the jet-veto efficiency, but a more detailed study is necessary.

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³In ref. [29] the authors report problems in describing the low p_t region with their NNLO parton shower approach.